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Radial Evolution of the Solar Wind Turbulence
with Application to Charged Particle Transport

to

Bartol Research Institute
of the University of Delaware

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Charles W. Smith, Principle Investigator

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(NASA-CR-194081) RADIAL EVOLUTION
OF THE SOLAR WIND TURBULENCE WITH
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The proposed research efforts funded by the Pioneer-Venus Guest Investigator Grant to the Bartol Research Institute center on a study of the radial and temporal variation of the large-scale interplanetary magnetic field (IMF) and include a study of the radial variation of the observed north-south asymmetry of the IMF spiral based on the previous results of Bieber [1988]. The preliminary results of Bieber demonstrated that at Earth orbit there exists an asymmetry between the yearly average winding angles of toward and away sector fields that can be as large as 10° . The Bieber [1988] analysis employed the NSSDC omnitape data set of 1 AU measurements. When the observed asymmetry is related to the state of the solar magnetic dipole, it is possible to conclude that the IMF north of the heliospheric current sheet is more tightly wound than the IMF spiral south of the current sheet. The average difference in the winding angle as measured over a 21 year period spanning 1965 through 1985 was $3.1^\circ \pm 1.1^\circ$. The Bieber analysis was able to rule-out several possible sources for the observed behavior including a possible asymmetry in the solar wind speed or the observed hemispherical dependence of solar rotation.

The object of this research was to extend this previous result to include observations within the inner and outer heliosphere, to examine the radial dependence of the reported asymmetry, and to better resolve the possible source of the observations. The Pioneer-Venus Orbiter has proven to be the perfect monitor for the inner heliospheric observations. It has provided 9 years of continuous observations at a fixed heliocentric distance (except for those periods when the spacecraft was within the region of space where the magnetic field is influenced by the presence of the planet). Comparisons between the 1 AU observations recorded on the NSSDC omnitape and the 0.7 AU observations of the Pioneer-Venus Orbiter have greatly improved our understanding of the IMF winding angle asymmetry. Further comparison with outer heliospheric measurements have proven interesting, although less conclusive.

Overwinding of the IMF

In the process of investigating the IMF winding angle asymmetry, we realized two facts concerning the average winding of the IMF spiral. First, there is a strong solar-cycle dependence linked to the average wind speed. As

the wind speed varies with the solar cycle, the resulting winding angle of the field changes. However, the average winding angle consistently exceeds the Parker [1958] prediction by several degrees. We have examined 23 years of 1 AU observations as contained within the omnitape data set, 9 years of 0.7 AU observations as represented by the Pioneer-Venus Orbiter (PVO) data set, as well as 7 years of Voyager 1 observations. We see that the IMF spiral is consistently overwound by several degrees and attribute this to a small azimuthal component at the source boundary. This result is discussed in more detail in Smith and Bieber [1991a] and has been presented at several international meetings.

We have suggested one possible explanation for this overwinding that concerns the source boundary of the solar wind. It is generally regarded that the magnetic field is directed radially at the solar wind boundary (a location approximated by the Alfvén radius where the flow speed exceeds the Alfvén speed). This was the basic tenant of Parker [1958]. Smith and Bieber [1991a] suggests that a small deflection from the radial direction (on the order of 1°) can account for the several degree overwinding at 0.7 and 1 AU. This deflection was argued to result from sub-chromospheric, azimuthal fields that "leak" into the corona. These fields result from the known differential solar rotation. If sufficient leakage were to occur (by injection by flares, loops, etc.) then the correct azimuthal component could be added to the solar corona. Other possible sources of the azimuthal component are now being investigated.

North-South Asymmetry of the IMF

We have extended the Bieber [1988] analysis in several regards. Several aspects of the measured IMF have necessitated an extensive examination of the analysis techniques we employ. In part, the motivation for this examination comes from the apparent correlation between field intensity and winding angle: the more intense fields are wound to the greatest angles. Also, potential errors were introduced by the trajectories of the outer heliospheric missions. We have performed the analysis discussed below in several different manners and with several different definitions of the "average" sector winding angle. We have based the "average winding angle" on analyses that compute the yearly average of the winding angles of the hourly measurements, the winding angle of the yearly vector average of the hourly vector measurements, the winding angle for the yearly vector average of the unit vectors of the hourly measurements,

and the average difference between the hourly winding angle and the expected Parker [1958] prediction based on the observed wind speed. The analyses yield comparable results in all cases.

We have examined the newly revised omnitape data set and extended the 1 AU results to include 2 additional years of observations. We have applied the same analysis technique to the 9 years of Pioneer-Venus Orbiter (PVO) observations spanning the years from 1979 through 1987, as well as 7 years of Voyager 1 & 2 observations, 4 years of Pioneer 10 measurements, and 14 years of Pioneer 11 observations. The PVO observations confirm the results observed at Earth orbit and indicate that the local gradient of the asymmetry is small. Two very curious results of the PVO analysis are not yet understood. For some reason, the year 1985 demonstrates a very large asymmetry (approximately 18°) in the PVO data while the asymmetry at Earth orbit is only about 7° . Of greater interest is the fact that the average asymmetry at the Venus orbit is always algebraically greater than the asymmetry at 1 AU. This does not imply that the north-south asymmetry is necessarily greater: that result would be implied if the difference between the asymmetries at Venus orbit and Earth orbit changed sign with the changing solar dipole. It does not. Ultimately, this fact is likely to play a major role in our efforts to understand the source of the observed asymmetry.

A second aspect of our proposed analysis involves the comparison of the observed asymmetry in the inner heliospheric spiral to the observations recorded in the outer heliosphere. There, we initially found an asymmetry that changes sign with the southern spiral more tightly wound than the northern spiral, and growing to very large values (approaching 40° for several years at a time). These were the results of our Voyager 2 analysis. With such extreme results, we sought to obtain confirmation. We examined the same time period of Voyager 1 observations and found little if any correlation with the Voyager 2 results. We then examined Pioneer 10 & 11 observations, and have now concluded that residual errors in the detector offsets of all instruments is too great to allow this analysis to be performed on these data sets.

While in pursuit of the offset issue, we realized that all 4 outer heliospheric data sets contained correlated, non-Parker field components for the T-component (or azimuthal component) of the field. There is a consistent, non-zero average of the T-component out to approximately 10 AU observed by all 4 spacecraft that averages approximately -0.1 nT. We do not at this time understand the source of this field, but we believe it to be real.

A thorough treatment of the analysis and results is now being completed and should be submitted to the Journal of Geophysical Research in August of 1991. This paper includes the analysis of omnitape, PVO, Voyager 1 & 2, and Pioneer 10 & 11 data sets, and represents an exhaustive treatment of the subject. This work has been a long time in completion, had undergone many revisions and tests, and now awaits only the completion of an error analysis.

Future Efforts:

We are considering other means of introducing an azimuthal component to the magnetic field at the Alfvén radius in addition to the differential rotation arguments presented in Smith and Bieber [1991a] in the hope of explaining the overwinding results. One means involves the tensioning of magnetic field lines that is required to maintain corotation of plasma elements brought up to the Alfvén radius from below. This would also lead to azimuthal field components with the correct sign to account for the observations, and we are pursuing the necessary theoretical treatments that may support or refute this idea.

Our efforts to evaluate the various asymmetries of the IMF are ongoing, and although support from the PVO Guest Investigator Program is now concluded, this work continues and will continue for several years to come. A brief listing of the talks presented, meetings attended, and papers submitted under the support of the PVO Guest Investigator Program follows:

Publications:

Smith, C. W., and J. W. Bieber, Measurement of the North/South Asymmetry of the IMF Spiral: Dependence Upon Heliocentric Distance, Proc. XXI Internat. Cosmic Ray Conf. (Adelaide), 5, 304-307 (1990).

Smith, C. W., and J. W. Bieber, Solar Cycle Variation of the Interplanetary Magnetic Field Spiral", C. W. Smith and J. W. Bieber, Astrophys. J., 370, 435-441 (1991a).

Smith, C. W., and J. W. Bieber, Radial Variation of the North-South Asymmetry of the Interplanetary Magnetic Field Spiral, in preparation, (1991b).

(Scheduled:)

Smith, C. W., and J. W. Bieber, Observational Study of the IMF Spiral North and South of the Current Sheet, Proc. of Solar Wind 7, Germany, (1991c).

Seminars, Invited, and Contributed Talks:

Asymmetries in the Solar Wind, C. W. Smith, Pioneer-Venus Science Steering Group Meeting, NASA/Ames Research Center, Mountain View, California, March 1989.

The North/South Asymmetry of the Interplanetary Magnetic Field Spiral: Observations in the Outer Heliosphere, C. W. Smith and J. W. Bieber, Symposium on the Outer Heliosphere, Durham, New Hampshire, May 1989.

Measurement of the North/South Asymmetry of the IMF Spiral: Dependence Upon Heliocentric Distance, C. W. Smith and J. W. Bieber, XXI International Cosmic Ray Conference, Adelaide, Australia, Jan. 1990.

Solar Cycle Dependence of the Interplanetary Magnetic Field Spiral, C. W. Smith and J. W. Bieber, Spring Meeting of the American Geophysical Union, Baltimore, Maryland, May 1990.

North/South Asymmetry of the Interplanetary Magnetic Field Spiral: Radial Variations, C. W. Smith and J. W. Bieber, Fall Meeting of the American Geophysical Union, San Francisco, California, December 1990.

Observational Study of the IMF Spiral North and South of the Current Sheet, C. W. Smith and J. W. Bieber, Solar Wind 7, Germany, September 1991.